Modeling of Alcator C-Mod Divertor Baffling Experiments

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Modeling of Alcator C-Mod Divertor Baffling Experiments D.P. STOTLER, PPPL, C.S. PITCHER, C.J. BOSWELL, T.K. CHUNG, B. LABOMBARD, B. LIPSCHULTZ, J.L. TERRY, PSFC, MIT, R.J. KANZLEITER, LANL — Specific Alcator C-Mod discharges from the series of divertor baffling experiments are simulated with the DEGAS 2 Monte Carlo neutral transport code. A simple two-point plasma model is used to describe the plasma variation between Langmuir probe locations. A range of conductances for the bypass between the divertor plenum and the main chamber are considered. The experimentally observed insensitivity of the neutral current flowing through the bypass and of the D_α emissions to the magnitude of the conductance is reproduced. The current of atoms in this regime is being limited by atomic physics processes and not the bypass conductance. The simulated trends in the divertor pressure, bypass current, and D_α emission agree only qualitatively with the experimental measurements, however. Modifications to the plasma model that ameliorate the quantitative differences are discussed. A companion 1-D simulation is presented and compared with an analytic model that reproduces the experimentally observed current limiting behavior.

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- [ ] Prefer Oral Session
- [X] Prefer Poster Session

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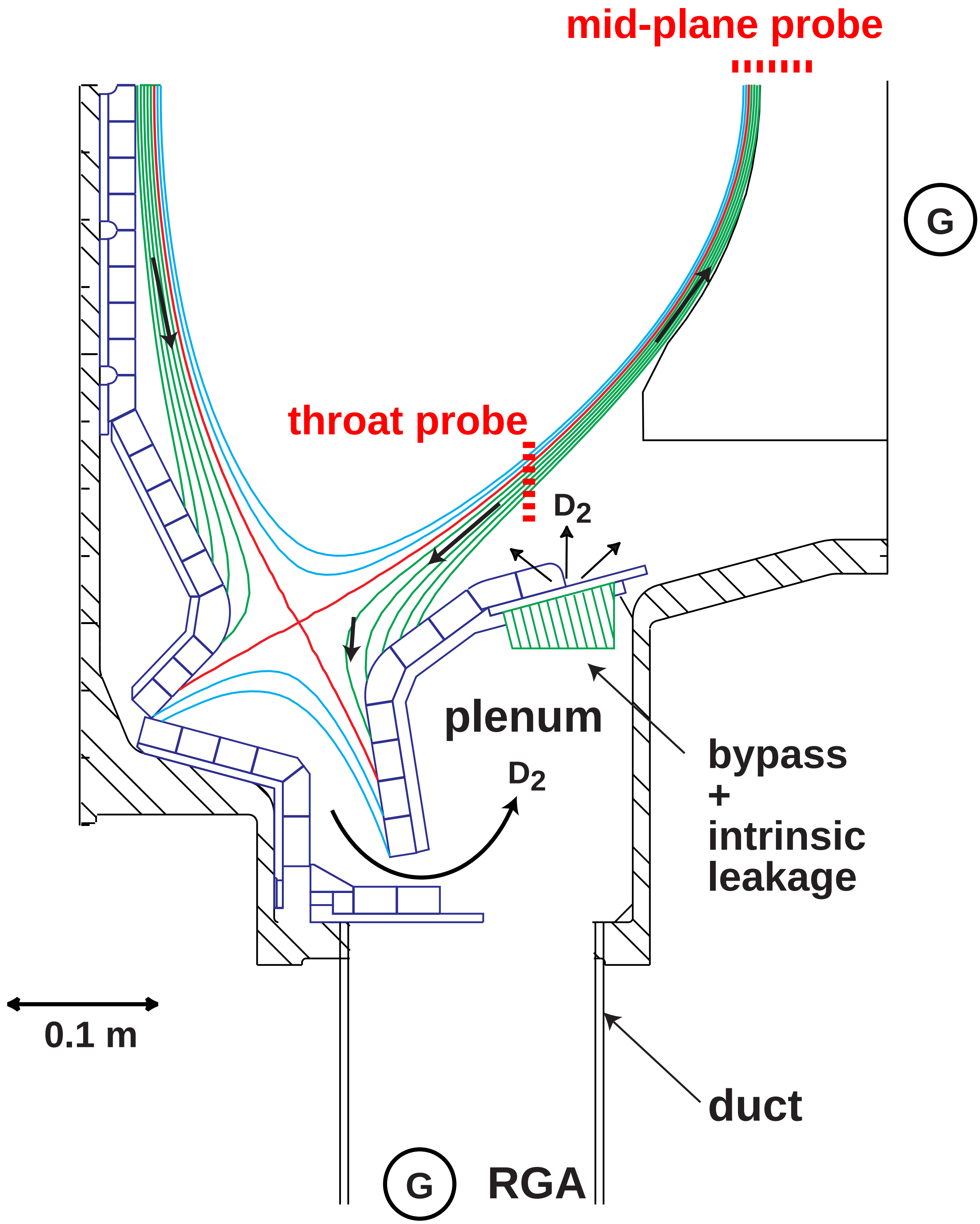
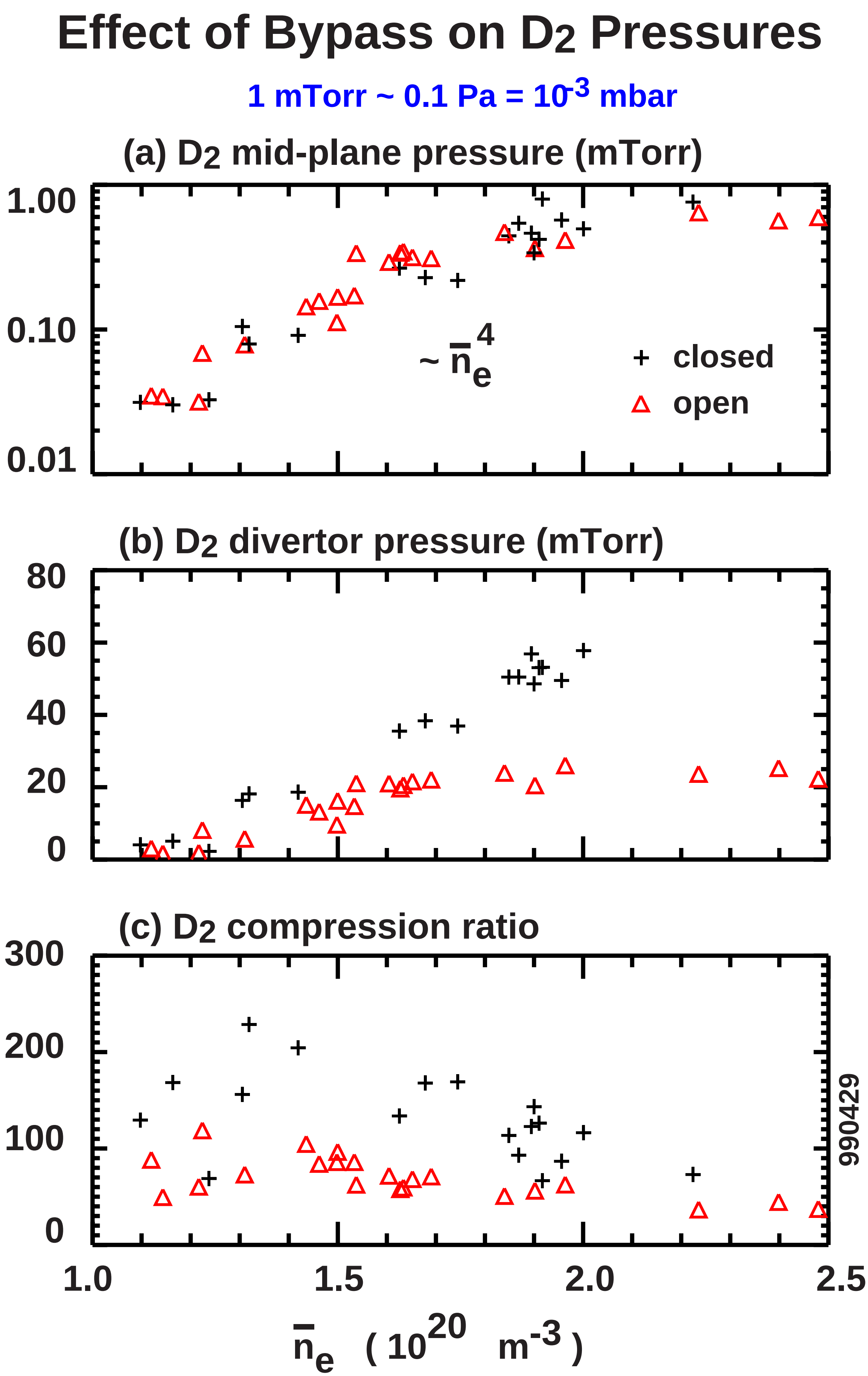
INTRODUCTION

- C-Mod divertor baffling experiments:
  - Change divertor - main chamber conductance by 2,
  - Divertor neutral pressure also changes by 2.
  - Infer that bypass current is constant!
  - Divertor plasma conditions and D_α do not change!
- Implies:
  - Atomic processes limit flow through bypass,
  - Divertor behaves as if it were completely open.
- Modeling requires:
  - Detailed treatment of geometry,
  - Kinetic treatment of neutrals.
  - $\Rightarrow$ use DEGAS 2 (Stotler 1992).
- Absence of effect on divertor plasma allows fixed plasma to be used,
  - Use Langmuir probe data,
  - And Two-Point model (Pitcher 1997).
- Find:
  - Insenstivity of bypass current for large conductances,
  - Dependence of pressure on conductance,
  - No change in D_α.
  - However, quantitative differences arise.

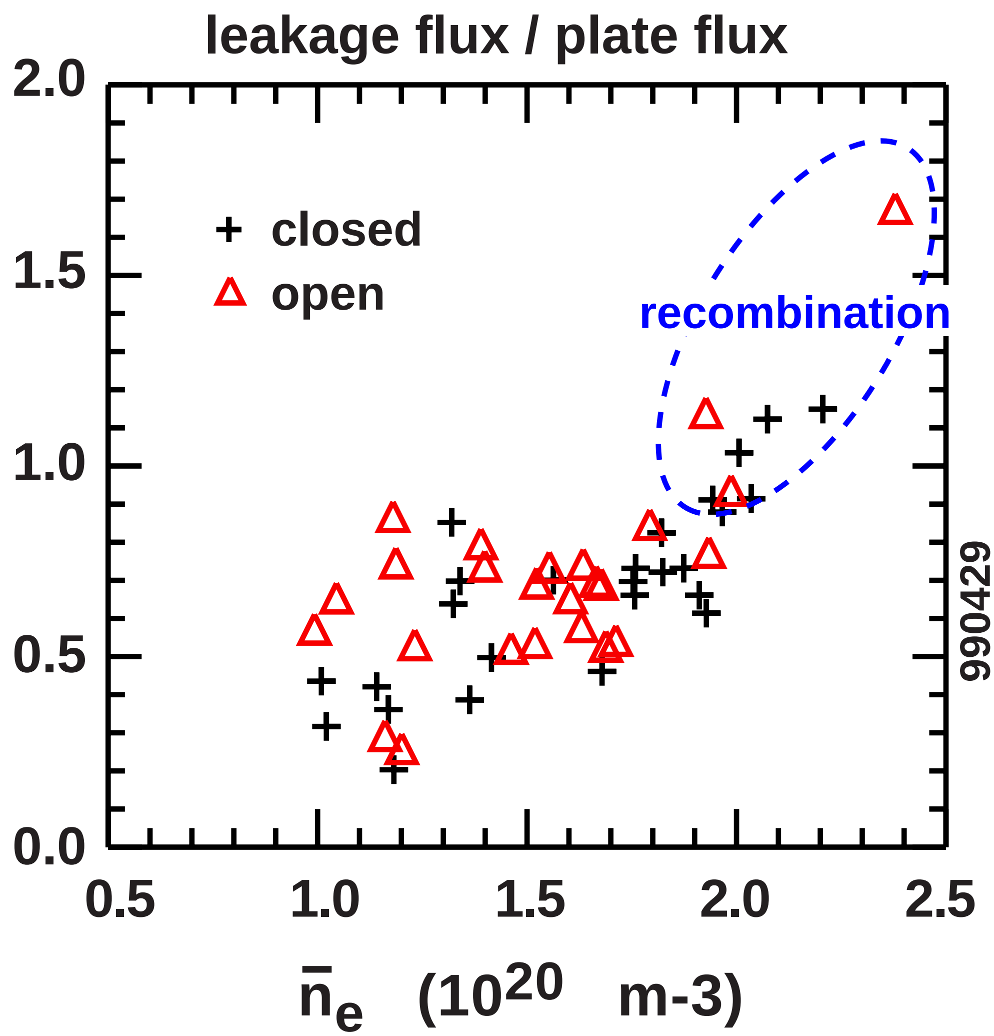
Alcator C-Mod Divertor Bypass





Effect of Bypass on D2 Pressures
1 mTorr ~ 0.1 Pa = 10-3 mbar
(a) D2 mid-plane pressure (mTorr)
1.00
0.10
0.01
~ ne 4
+ closed
△ open
(b) D2 divertor pressure (mTorr)
80
60
40
20
0
(c) D2 compression ratio
300
200
100
0
990429
1.0
1.5
2.0
2.5
ne (10 20 m-3)

Leakage Flux is comparable to ion flux to outer plate



this is surprising given that the C-Mod baffling is relatively closed, f ~ 0.15

EXPERIMENTAL DATA

- Divertor bypass experiments described in (Pitcher 2000).
- Focus on shot 990429019, $t = 0.95$ s,
  - $\overline{n}_e = 1.46 \times 10^{20}$ m^{-3},
  - Both targets in high recycling regime,
  - $P_{\rm div} = 15$ mTorr with bypass open,
  - $P_{\rm div} = 30$ mTorr with bypass closed.
- Plasma data from scanning probes at midplane & throat,
- Target data and fluxes from fixed Langmuir probes.
- Compare with divertor viewing D$_\alpha$ array
  - B-top, 63 detectors.

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- Plasma for DEGAS 2:
  - 1-D "Two Point" model for variation between probes,
  - Plasma pressure constant along flux surfaces,
  - Except in recycling region near target,
  - Pressure drops to target value,
  - Size estimated for these simulations.
  - Parameters in PFR interpolated between inner & outer values.
  - $n_e = n_i$, $T_e = T_i$, no impurities.
  - Plasma outside computational mesh:
    - 4 cm radial density decay,
    - constant T.
- Main chamber source:
  - Simulate recycling on limiters in main chamber (Umansky 1998),
  - Calculate using

$$\Gamma = \frac{1}{4} n_{D_2} \sqrt{\frac{8 T_{\rm wall}}{\pi m}},$$

  - With $n_{D_2} = P_{\rm main} / T_{\rm wall}$,
  - Use measured value $P_{\rm main} = 0.15$ mTorr.

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DESCRIPTION OF SIMULATION

- Geometry
  - Outline of vacuum vessel, including
    - Divertor plenum,
    - Lower port,
    - RF limiter.
  - EFIT equilibrium,
  - Loaded into DG,
  - Generate plasma mesh with CARRE,
  - Transfer "elements" and plasma mesh to *definegeometry2d*,
  - Polygons broken up into triangles with *Triangle* (Shewchuk 1996),
  - Polygons labeled with zone number,
  - Converted to DEGAS 2's internal "surfaces" and "cells".
  - Conductance between divertor, duct, and plenum approximate.
- Bypass width w,
  - $w = 16$ mm $\rightarrow$ integrated area of 0.075 m^2,
  - Corresponds to bypass *closed* .
  - With bypass *open* , total area estimated 0.150 m^2, $\Rightarrow w = 32$ mm ,
  - Also consider $w = 0$, 8, and 64 mm.
  - $w = 0 \leftrightarrow$ ideal of closed divertor.

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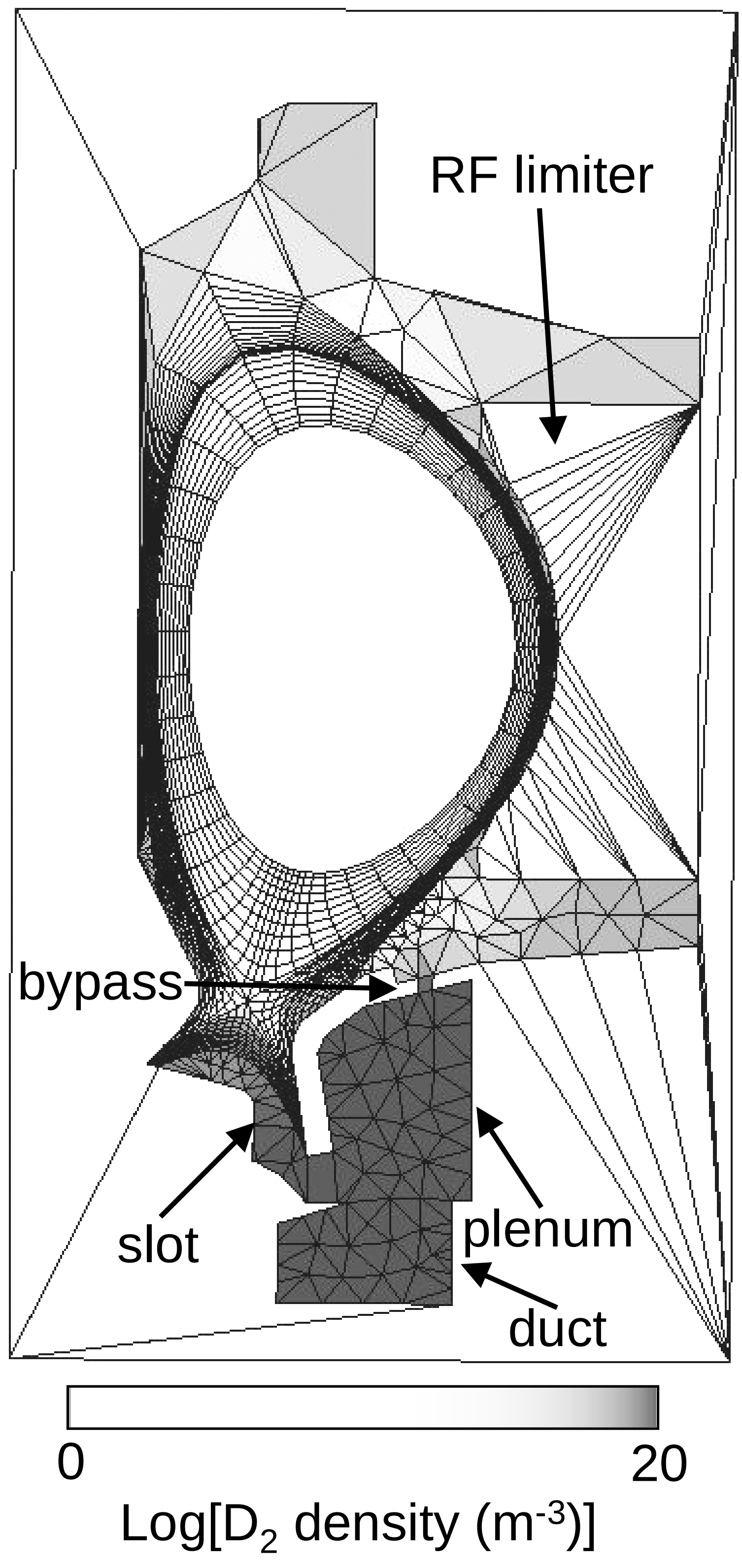
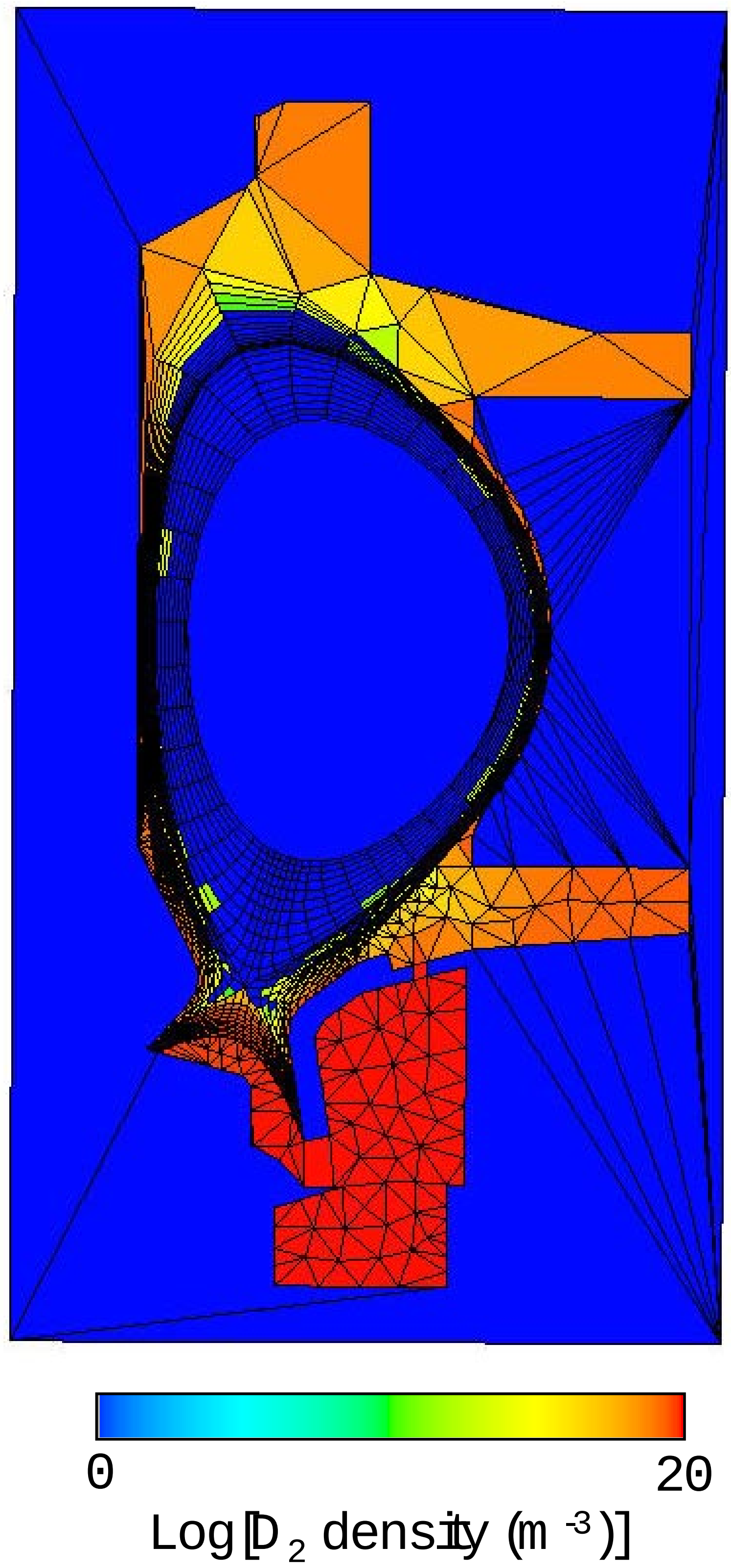


Fig. 1



0
20
Log[D_2 density (m^{-3})]

- All surfaces assumed to be molybdenum,
  - Reflection coefficients from TRIM, 0.5–0.6.
  - Non-reflected atoms desorb as thermal molecules.
- Atomic Physics
  - Collisional-radiative model for D ionization & recombination,
    - Based on (Weisheit 1975),
    - Cross sections taken from (Janev 1993),
    - Optically thin,
    - Assess opacity effects later using escape factor (e.g., Terry 1998).
  - Molecular rates and kinetics as in (Stotler 1996),
    - No D_α from molecules (10% effect).
  - Ion-neutral scattering,
    - Differential cross sections computed using quantum mechanical techniques (Krstic 1998),
    - D + D^+ incorporates CX & elastic scattering,
    - Include D_2 + D^+,
    - Enforce minimum scattering angle,
      - But constrain momentum transport to not change (Kanzleiter 1999),
    - Use cumulative probability tables for cosine of scattering angle (Kanzleiter 1999).

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– Neutral-neutral elastic scattering,
  * BGK treatment just as in (Reiter 1997),
  * Knudsen numbers,
    · ~ 0.01 for molecules in plenum,
    · > 1 for atoms in slot,
    · $\Rightarrow$ Need nonlinear kinetic treatment.
– Running on 18 processor PC cluster (Stotler 2000),
  * Single iterations $\sim$ few minutes,
  * Few to several iterations required.

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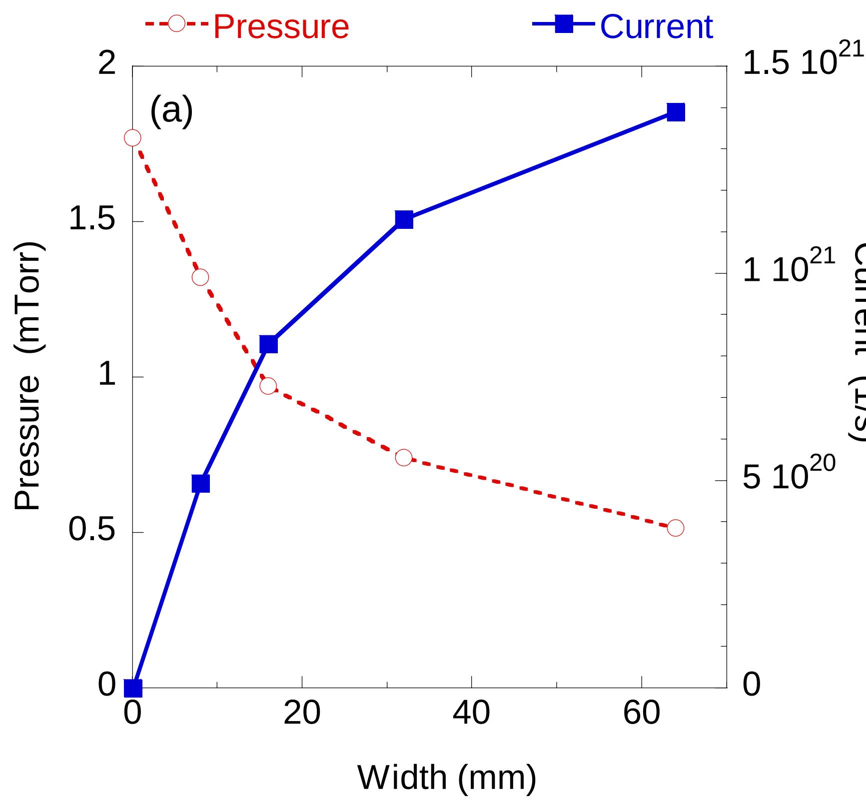
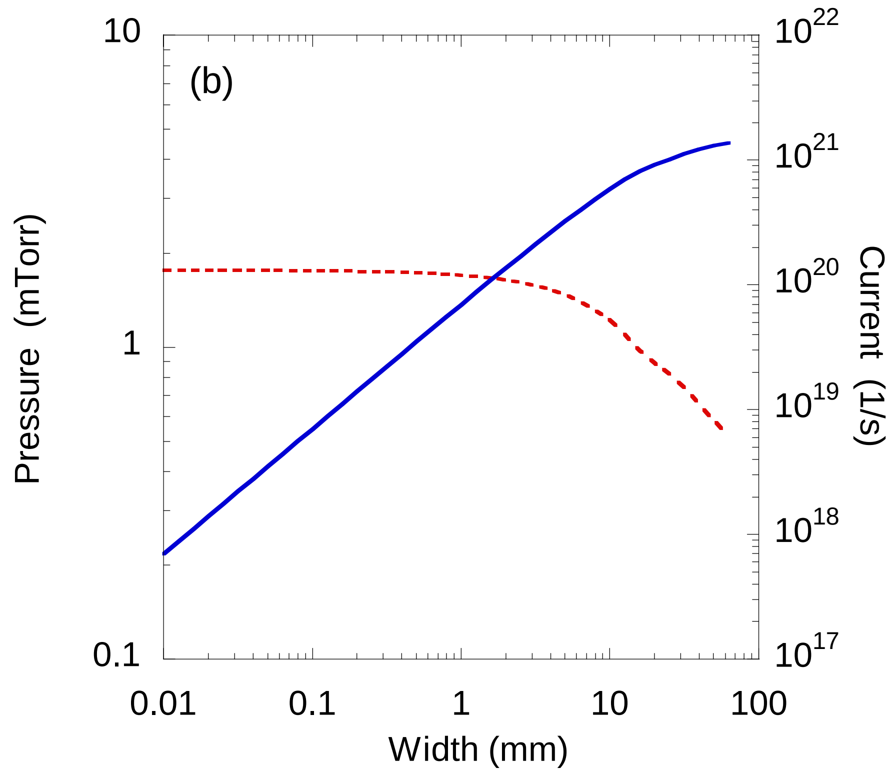
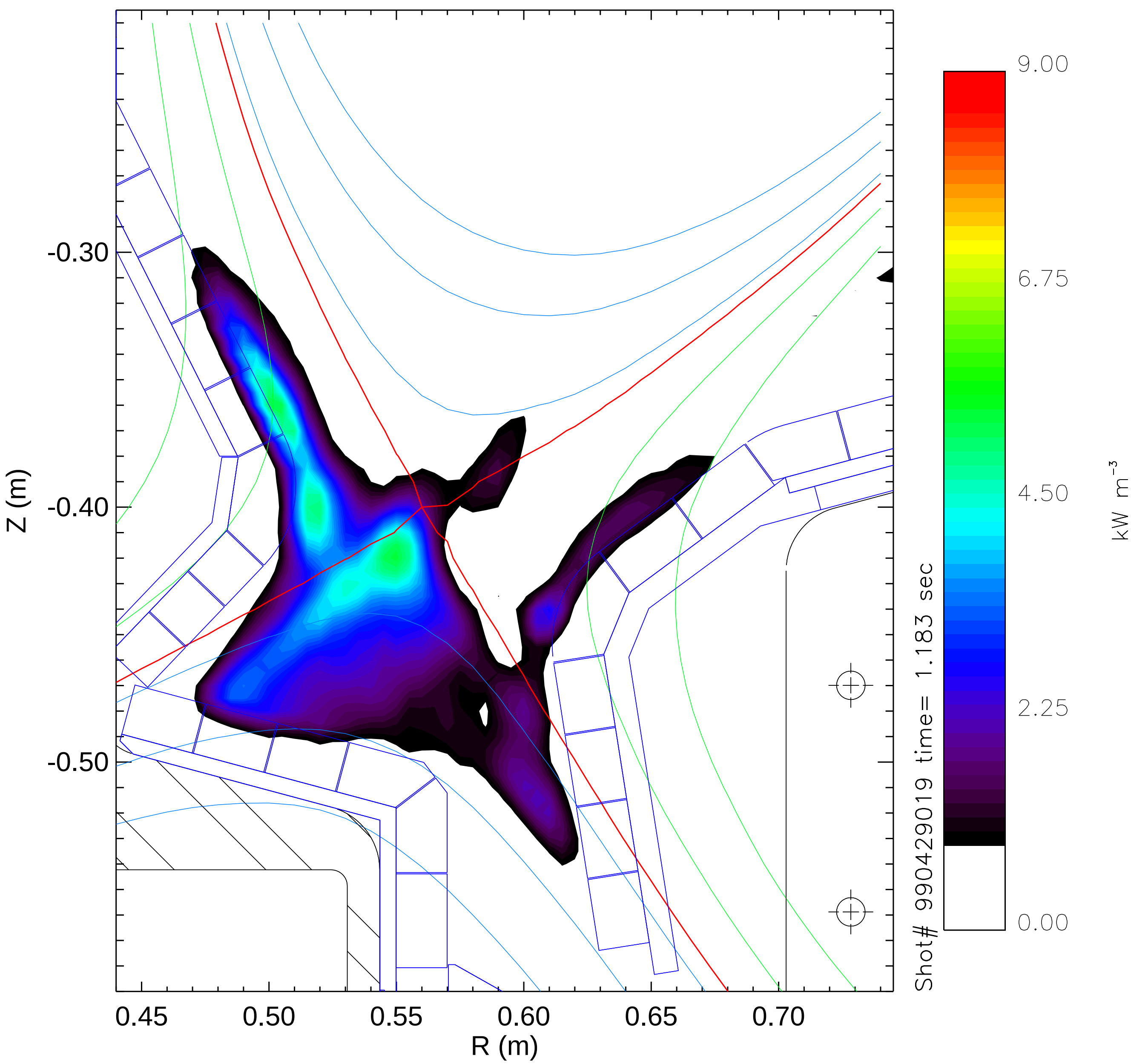
RESULTS

- Plot plenum pressure P and bypass current ϕ vs. w,
  $\Rightarrow$ "Baseline" Plot
- $\phi \ll$ ion current to target $= 1.60 \times 10^{22}$ s^{-1}
- Compare D$_\alpha$ with measurements,
  - Simulation results show no dependence on w,
  - Emissions dominated by regions far from slot,
  - And because ϕ small.
- Plenum pressures $\sim$ order of magnitude too small,
- D$_\alpha$ is a factor of 3 – 10 too small,
- Possible explanations:
  - No reason to suspect Langmuir probes off by > 2,
    - ∗ But, earlier neutral particle balance encountered similar difficulties (Niemczewski 1995).
  - Recombination in private flux region
    - ∗ D$_\gamma$ tomography indicates more than obtained with simple plasma model for PFR,
    - ∗ Assess effect by adjusting plasma to match peak,
      - · Recombination source $\sim$ outer target current,
      - · D$_\alpha$ plotted,
      - · $P \uparrow$ from 0.97 mTorr ("closed" bypass) to 1.88.
      - · Recombination nearer outer target may have larger effect.

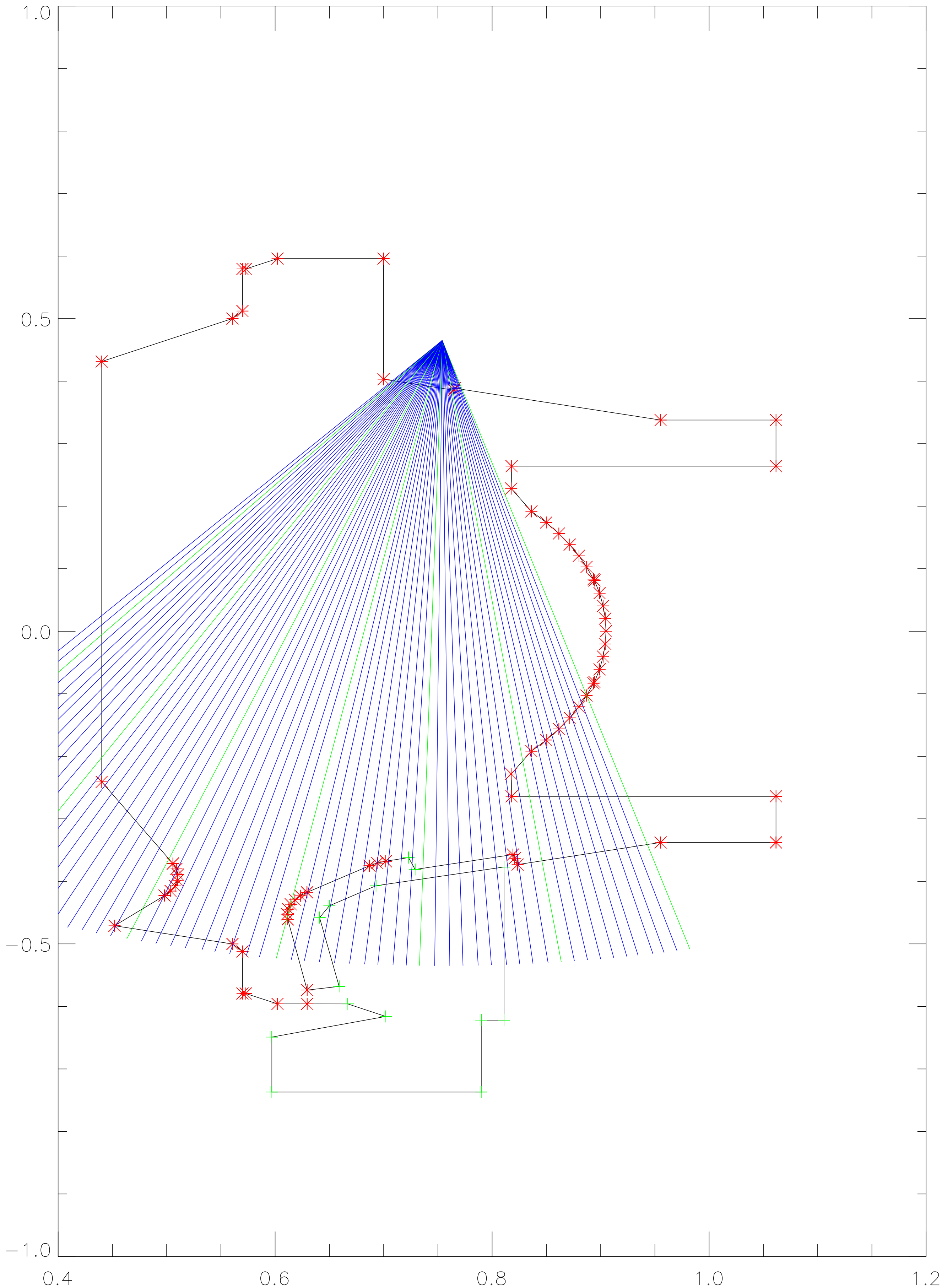
Width Scan with Baseline Plasma



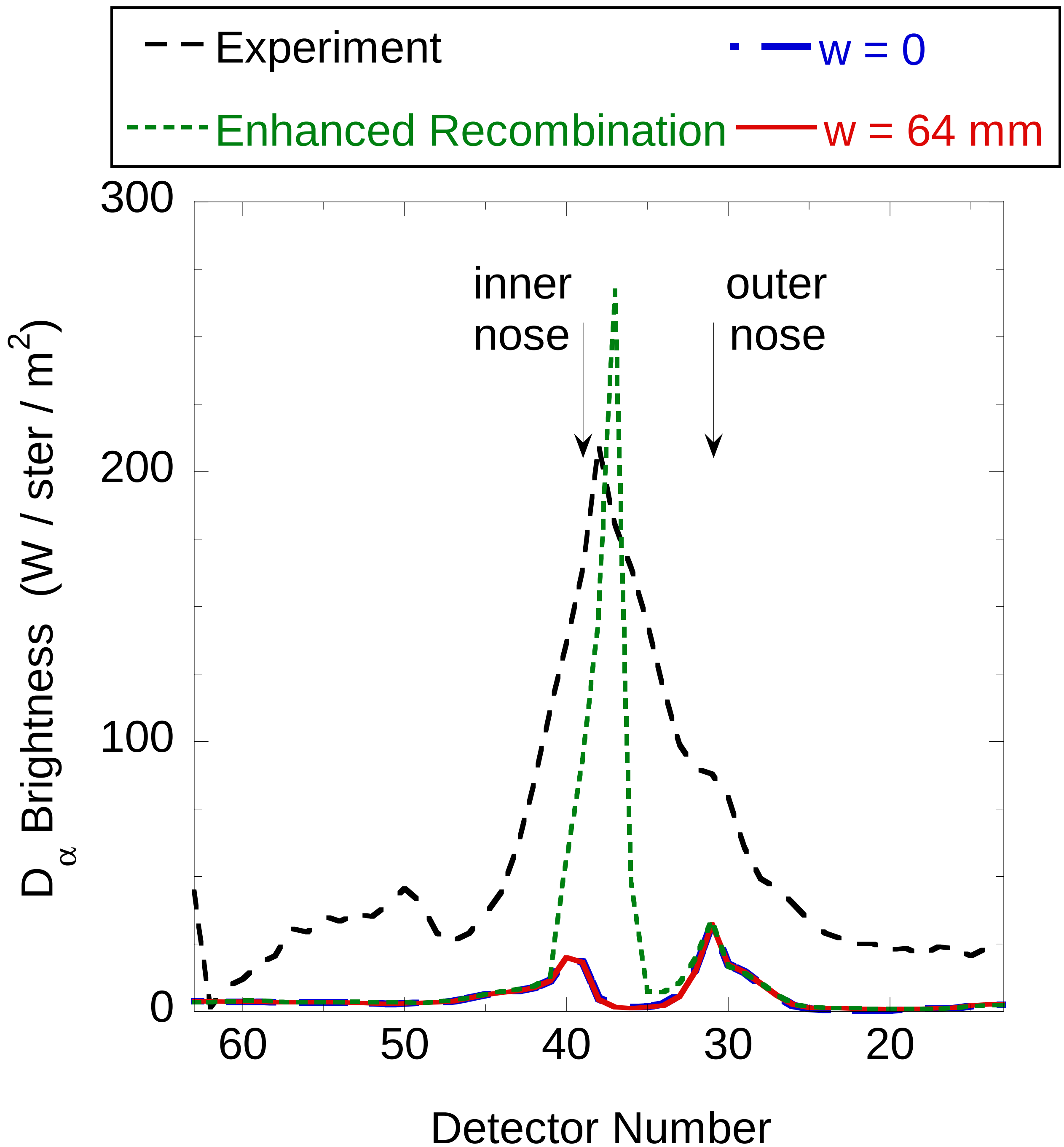




Z (m)
-0.30
-0.40
-0.50
R (m)
0.45
0.50
0.55
0.60
0.65
0.70
9.00
6.75
4.50
2.25
0.00
kW m^{-3}
Shot# 990429019 time= 1.183 sec



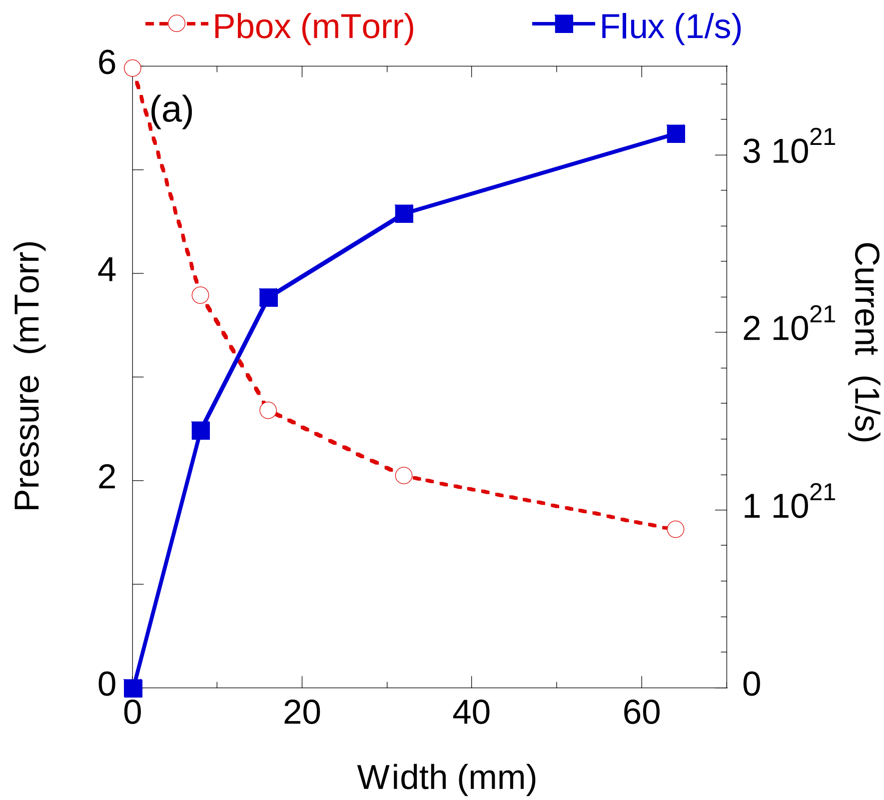
1.0
0.5
0.0
−0.5
−1.0
0.4
0.6
0.8
1.0
1.2

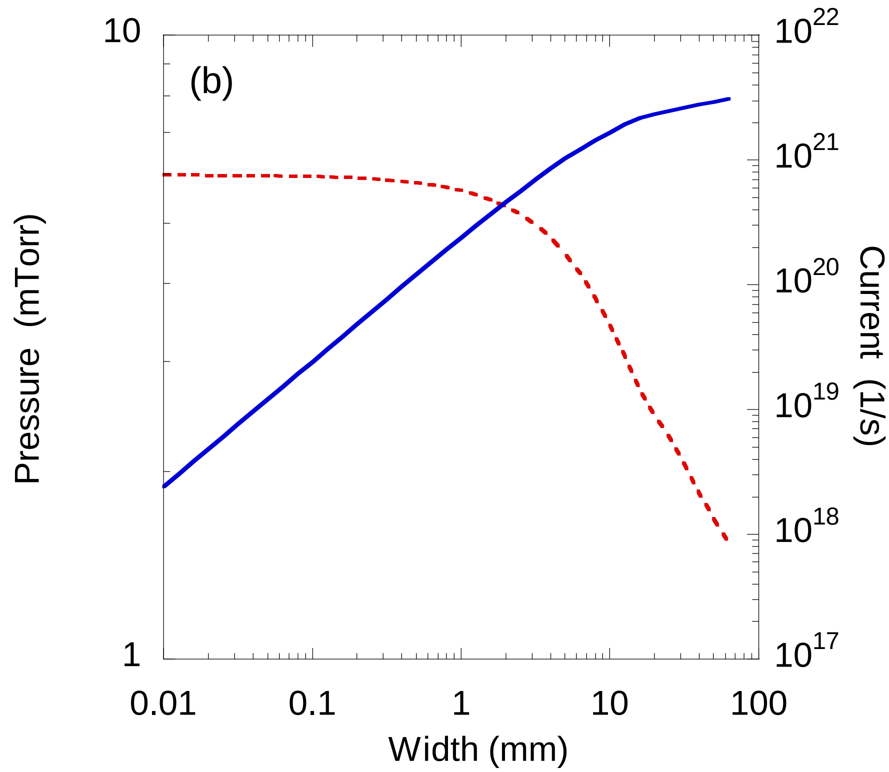


Experiment
w = 0
Enhanced Recombination
w = 64 mm
300
200
100
0
inner nose
outer nose
60
50
40
30
20
Detector Number
D_α Brightness (W / ster / m^2)

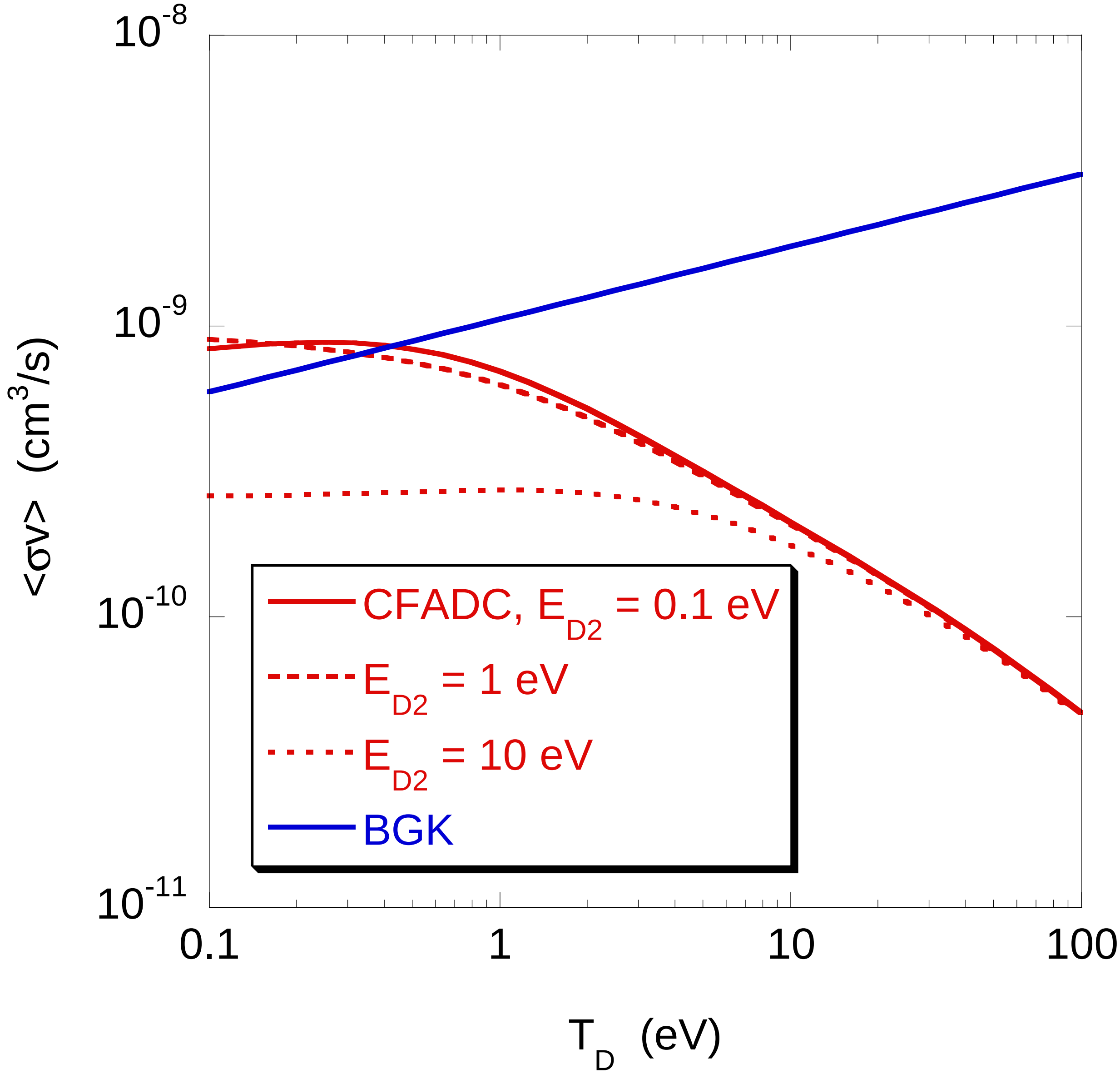
- Treatment of recycling region,
  - Size of region and density peak only estimated,
  - Errors could overemphasize ionization,
  - Should iterate DEGAS 2 & plasma model,
  - Bound magnitude of effect by capping n and T at 1×10^{20} m^{-3} and 4 eV,
    - See second plot
    - P and $\phi \uparrow$ by 2,
    - D$_\alpha$ less affected.
- Treatment of neutral-neutral scattering still being benchmarked,
  - Is working correctly qualitatively,
    - Set up test simulation with target fluxes enhanced by 10,
    - $\Rightarrow P = 12.5$ mTorr,
    - Turn off neutral-neutral scattering: $P = 6.3$,
    - Turn off molecule-ion scattering: $P = 5.4$.
  - Reaction rate used in BGK model of D + D$_2$ (Reiter 1997) right order of magnitude,
    - Plot with expected momentum transfer rate,
    - Integral of fully quantal differential cross sections from CFADC (Krstic 1998).
    - BGK T_D dependence comes from fit to experimental diffusion data $\Rightarrow$ may want to revisit.
  - Want to repeat Reiter's temperature equilibration and Couette flow tests, too.

Width Scan with $n_e \leq 10^{20}\ m^{-3}$, $T \leq 4$ eV





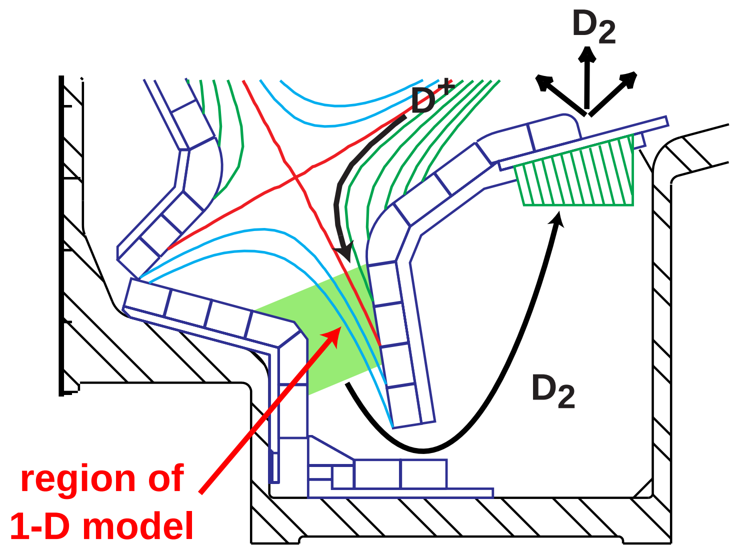
D + D_2 BGK Rate Similar to Momentum Transfer Rate from CFADC $d\sigma/d\Omega$, but Different T Dependence

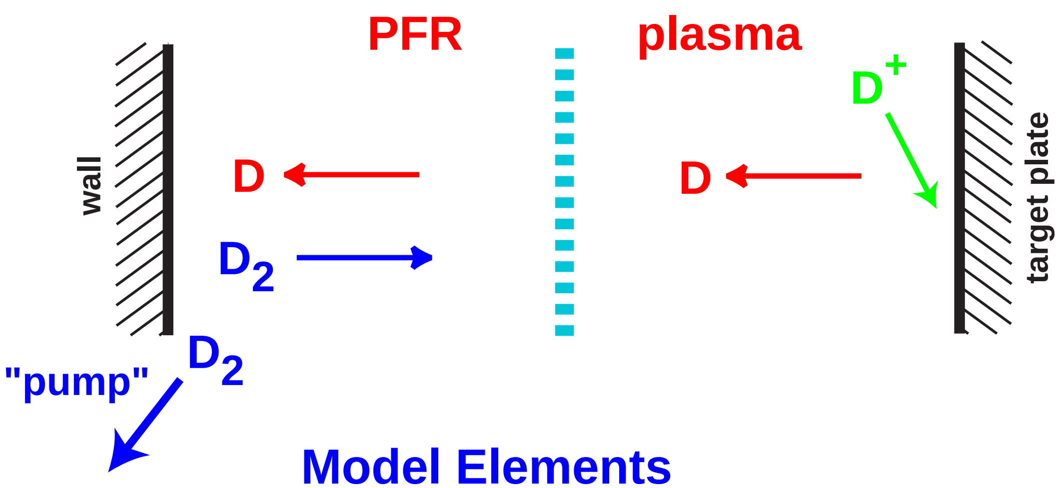


1-D MODELS

- Compare P, ϕ with Pitcher's 1-D model (Pitcher 2000a),
  - Replot data on log-log scale,
  - Closely resembles Fig. 7 of (Pitcher 2000a),
  - Quantitative differences arise.
- "Flux limited" regime arises for $w \gtrsim 10$ mm,
  - ϕ determined by competition between divertor ionization and escape through bypass,
  - At large enough w ionization & CX limit ϕ,
  - $\Rightarrow$ open divertor.
- "Conductance limited" for $w < 10$ mm,
  - Linearly varying ϕ with w,
  - Insensitive pressures.
- Compare details with 1-D slice through DEGAS 2 geometry (see red box on sketch),
  - Bypass closed with $n_e \leq \times 10^{20}$ m^{-3} and $T \leq 4$ eV.
  - Qualitative similarities for D,
  - But D_2 quite different.

Simple 1-D Model





Model Elements

- atom, molecule: continuity, momentum
- plasma: ionization and CX
- PFR: momentum exchange between D and D_2

Boundary Condition ("Pump Fraction" = f)

$$f_{pump} = \frac{1}{4} n_{mol} \bar{c}_{mol} f$$

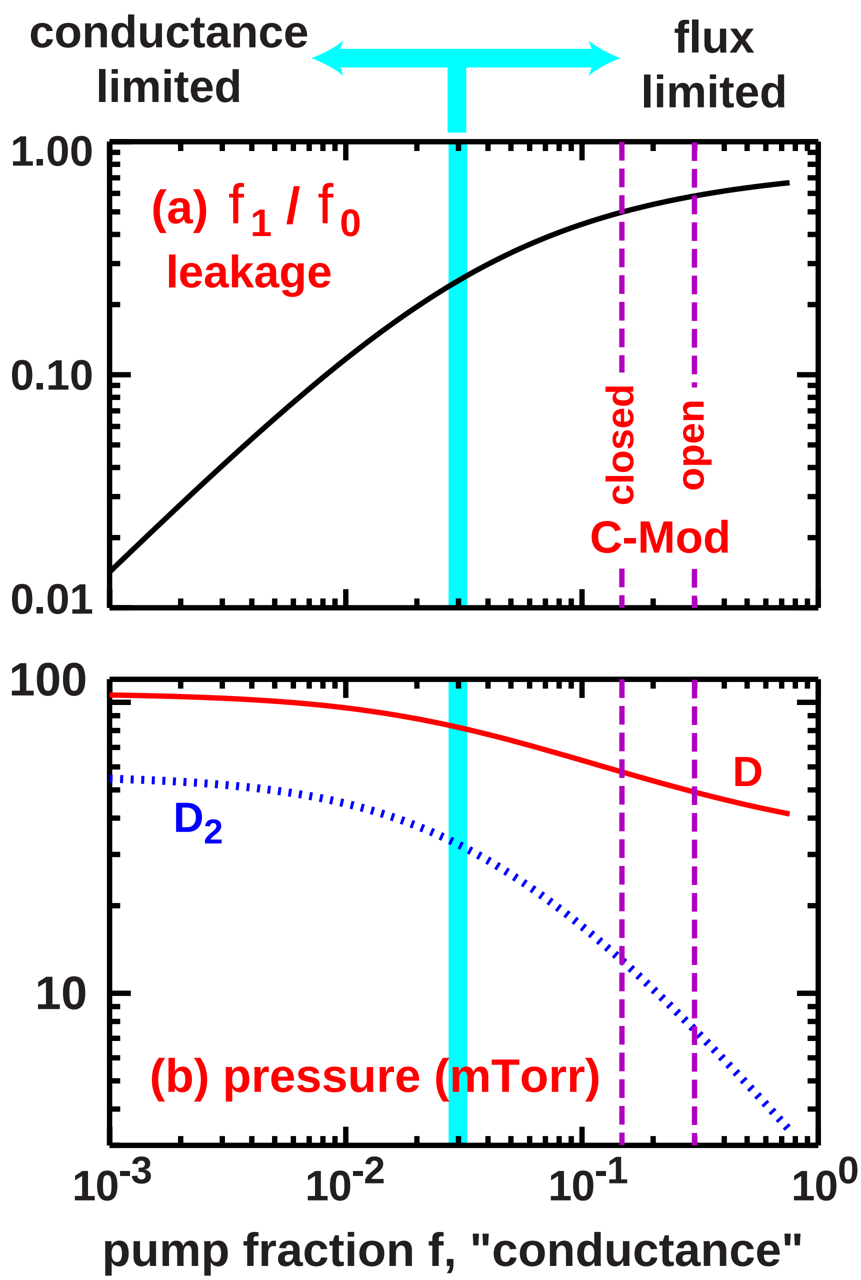
Two Regimes of Operation

(1) conductance limited

leakage ~ f, pressure ~ const.

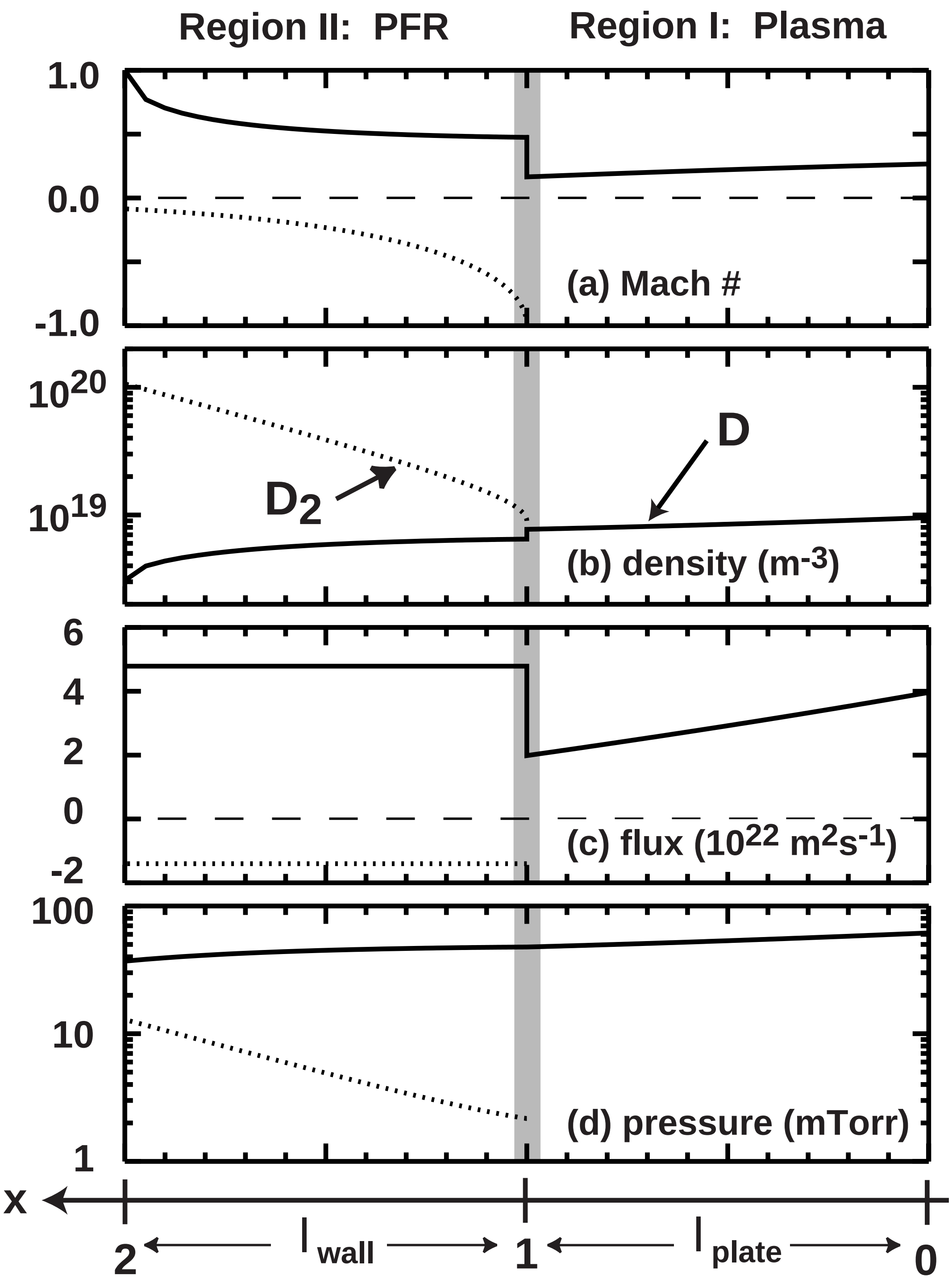
(2) flux limited

leakage ~ const., pressure ~ 1/f



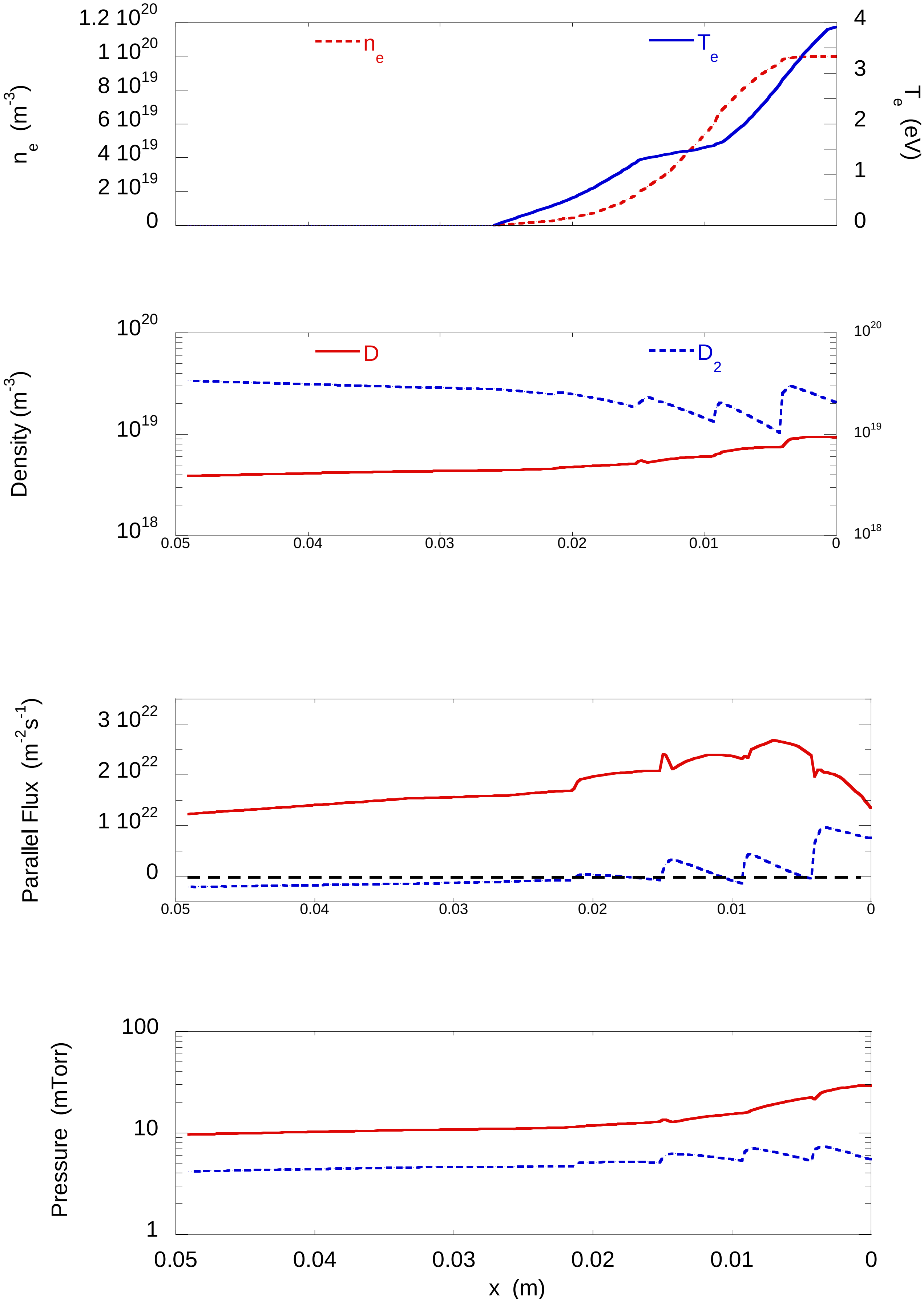
note: confirmed using DEGAS 2, see Stotler, P-2.59

Fig. 7



Region II: PFR
Region I: Plasma
1.0
0.0
-1.0
(a) Mach #
10^{20}
10^{19}
D
D_2
(b) density (m^{-3})
6
4
2
0
-2
(c) flux (10^{22} $m^2 s^{-1}$)
100
10
1
(d) pressure (mTorr)
x
2
l_{wall}
1
l_{plate}
0

1-D Slice Taken from DEGAS 2 with Closed Bypass



- Further reduce differences using separate 1-D DEGAS 2 simulation,
  - 1-D box with 0.5 cm plasma, 10 cm vacuum,
  - $n_e = 1.8 \times 10^{20}$ m^{-3}, $T = 5$ eV,
  - "Puff" source of D at 4×10^{22} m^{-2} s^{-1} at target,
  - 3 walls mirrors,
  - 4th ("PFR")has 15% absorption,
    - Everything else comes back at 0.1 eV molecules.
  - Atomic Physics:
    1. Ionization,
    2. D + D$^+$ elastic scattering,
    3. D_2 dissociation (*no other molecular processes*),
    4. All neutral-neutral scattering processes,
       - Use $\langle \sigma v \rangle_{D,D_2} = 2 \times 10^{-9}$ m^3 s^{-1} to match (Pitcher 2000a).
  - Arguably in quantitative agreement!
  - Suspect geometry is dominant difference from full simulation,
  - $\Rightarrow$ eliminate other physics differences & check.

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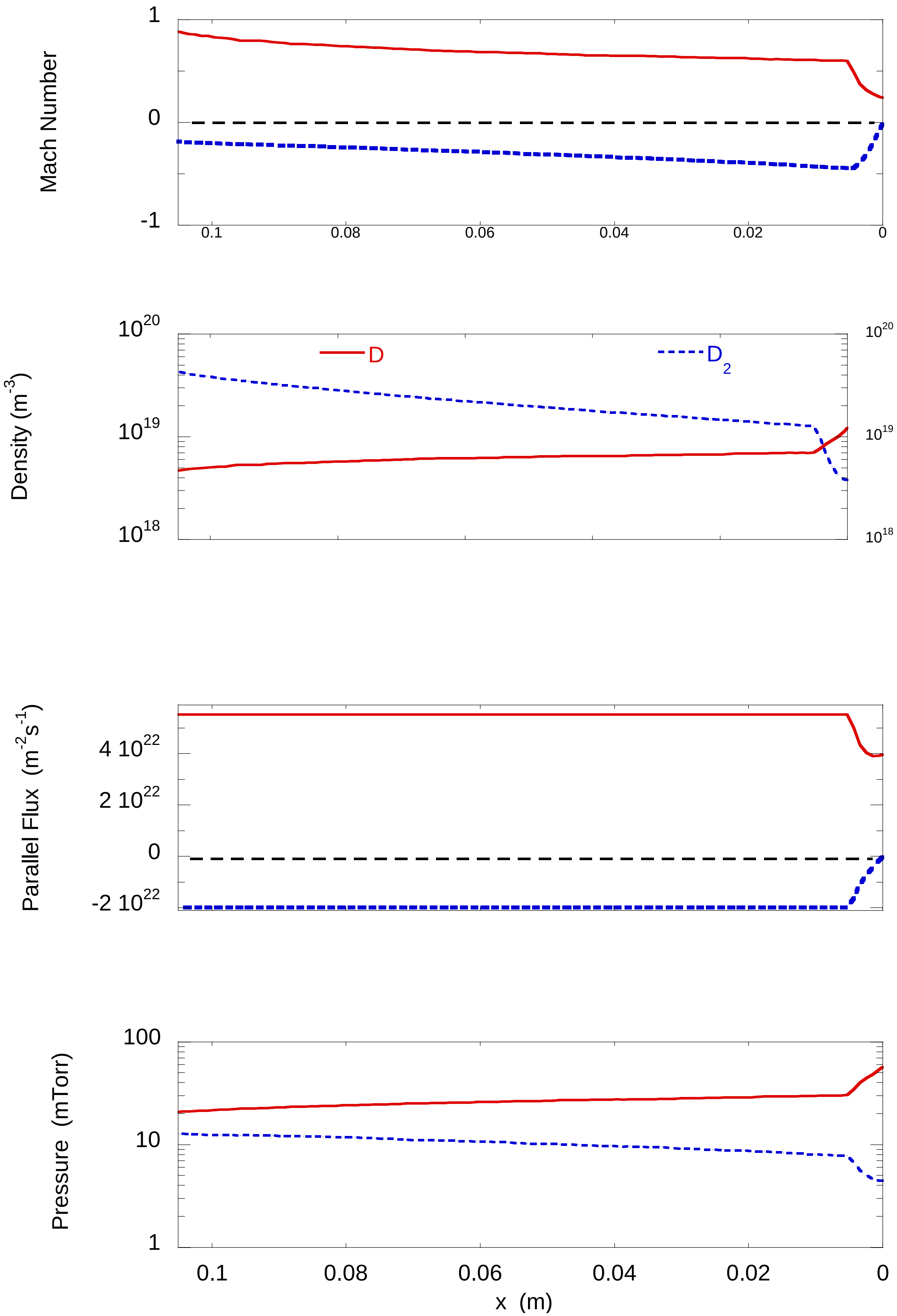
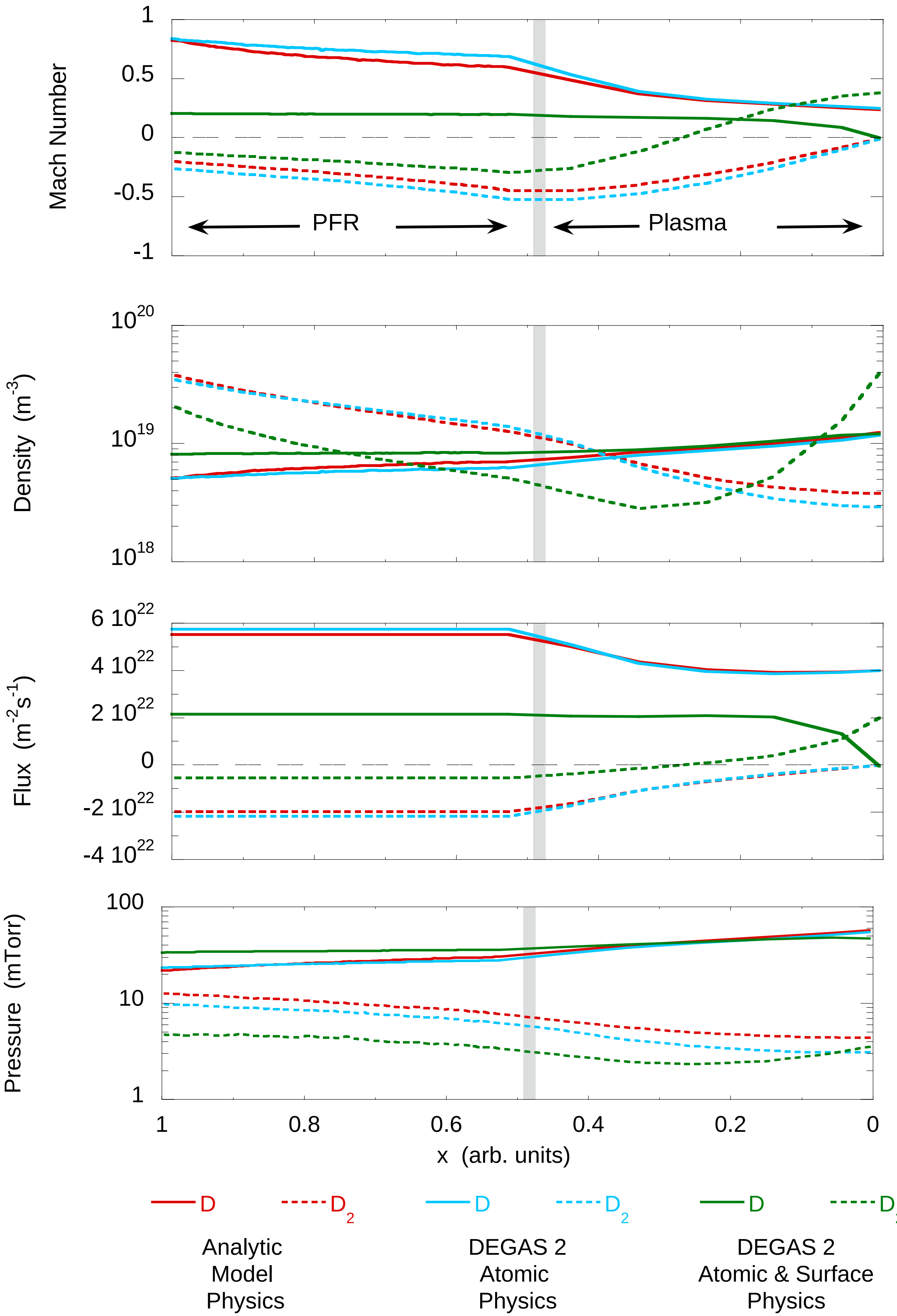
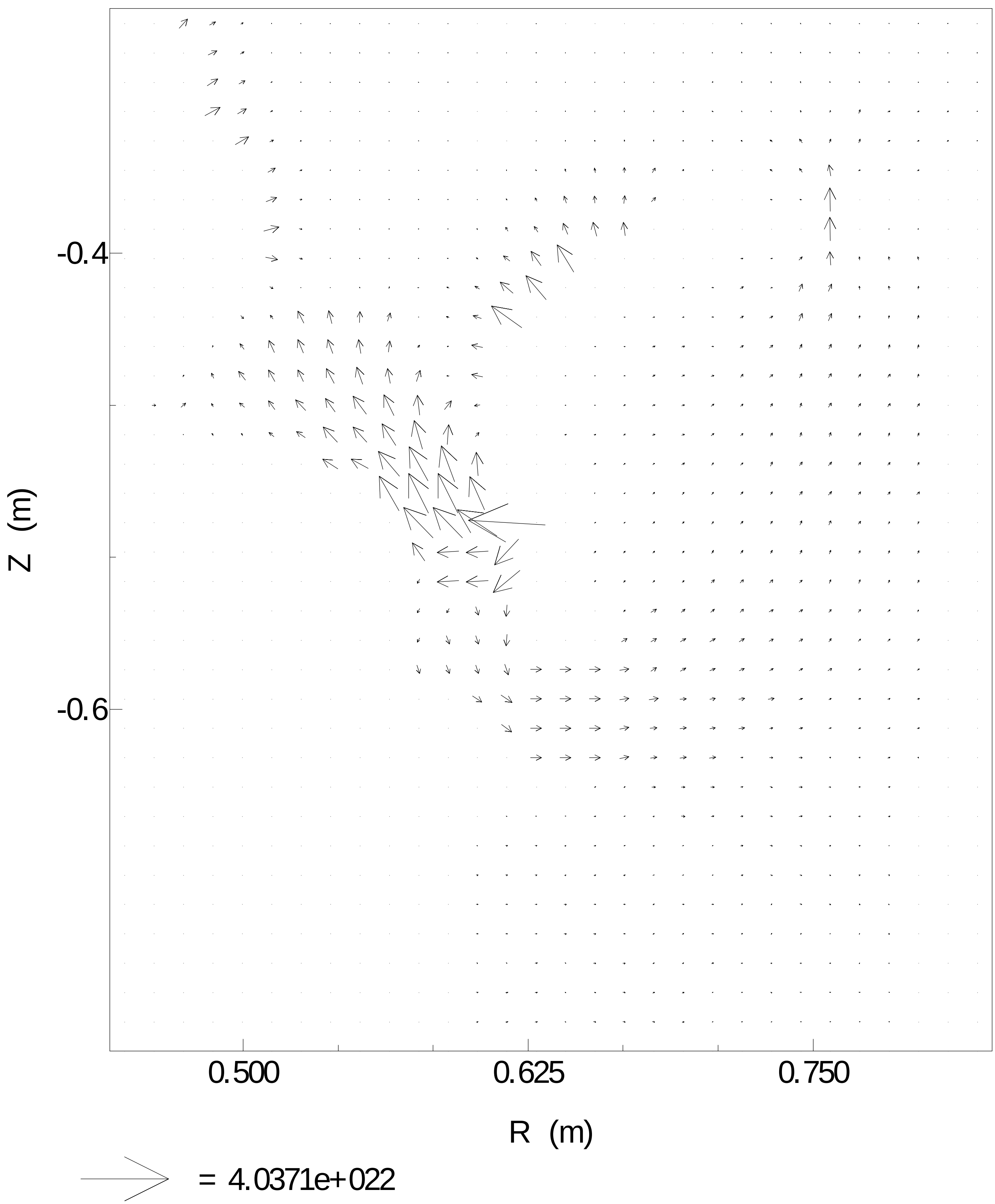
Separate 1-D DEGAS 2 Model Matches Pitcher's 1-D Model Well



1-D DEGAS 2 Run Matches Analytic Model with Same Physics
Using Full Surface Physics Yields Lower D_2 Pressure



Total D Flux Vectors in w = 16 mm Baseline Simulation



CONCLUSIONS

- Experimental results:
  - Bypass strongly affects neutral pressure,
  - But not bypass current,
  - Plasma conditions and D_α do not change.
- Principal result here:
  - Reproduce same qualitative trends,
  - Decreasing sensitivity of ϕ with w
    $\Rightarrow$ some other process limiting flow,
  - Conclude: divertor effectively open.

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